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Development and evaluation of portable and wearable fuel cells for soldier use

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HIGHLIGHTS

- Test and evaluation of systems developed for portable and wearable military applications.
- Laboratory results and soldier feedback from limited test events included.
- Portable FC systems require power density improvements for widespread use.
- Based on feedback, desirable wearable system attributes include thin form factor.
- Wearable systems based on Alane demonstrated high power density offering an attractive power source.

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ABSTRACT

A number of fuel cell systems have been recently developed to meet the U.S. Army's soldier power requirements. The operation and performance of these systems are discussed based on laboratory results and limited soldier evaluation. The systems reviewed are primarily intended for soldier use in an austere environment with minimum access to resupply and vehicular transportation. These applications require high power and energy density sources that are portable (300 W) and wearable (20 W) to minimize the soldier's load burden. Based on soldier field evaluations of portable fuel cell systems, improvements in power density and compatibility with logistical fuels are required to be successfully deployed. For soldier worn applications, a novel chemical hydride system has shown significant advances in power and energy density while maintaining a small form factor. The use of a high energy dense fuel cartridge (800 Wh kg^{-1}) based on AlH_3 (Alane) thermolysis, allows a power density of (28 W kg^{-1}) which offers promising weight savings compared to the standard military batteries.

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1. Introduction

Power and energy are critical to the modern soldier. Power sources enable communications and situational awareness capabilities such as the tactical war fighter information network (WIN-T) and the Nett Warrior system. These capabilities allow the soldier continuous access to a secure mobile network without the need for a fixed infrastructure potentially resulting in improved mission execution.

The aforementioned capabilities are especially valuable to applications with minimum access to resupply and vehicular transportation, generally referred to as *dismounted soldier* use in an austere environment. The austere environment may include limited access to a reliable source of electricity, environmental hazards (e.g. heat, cold, altitude) without climate control, and operation with the prolonged use of body armor [1]. However, to effectively deploy these capabilities on the dismounted soldier, the soldier's total gear weight cannot increase, as higher weight leads to lower mobility and increased risks of musculoskeletal injuries [2–4]. This requirement has resulted in the US Army, together with other government agencies and industrial partners, supporting fuel cell development [5–10] resulting in a number of fuel cell prototypes. The application, operation and performance of these fuel cells systems, specifically for dismounted soldier applications, are discussed in this article.

1.1. Previous work

Recently Shaw et al. [11] investigated requirements for man portable systems and identified military personnel power

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generators, consumer battery rechargers, and specialized laptop computers as potential applications of fuel cell technology. A significant commercialization barrier identified was the lower energy density of H_2 storage systems vs. batteries, resulting from low H_2 storage capacity and fuel cell system components.

Earlier reviews of portable fuel cells [8,12,13,14] have discussed the application of methanol based fuel cells to the US Army for power requirements less than 500 W. Previous work on these systems included the development of micro channel based methanol reformers in a small form factor for methanol based fuel cell.

This article discusses the performance and application of recently developed methanol/propane and chemical hydride based fuel cell systems for military use.

1.2. Description of power sources for dismounted soldier use

Similar to the civilian market, the US military's incumbent solution for portable and wearable power is battery technology. The advantages of low life cycle cost, logistics simplification and mature technology have resulted in rechargeable batteries being accepted by the Army and partially displacing primary batteries. However, major drawbacks of the existing rechargeable technology are: the requirement for a recharging infrastructure; the relatively lower energy density of these systems vs. primary systems. Both of these attributes are undesirable on the modern battlefield.

Fuel cells offer a potential solution to these issues. Their use of high energy density fuels, which can be packaged as replaceable cartridges, offers significant weight savings for extended mission duration. For dismounted soldier use, fuel cell systems can be utilized in two distinct applications as described below.

1.3. Description of fuel cell applications for the dismounted soldier

A *portable* fuel cell would be utilized as an auxiliary power unit (APU) for recharging batteries. These units can meet the need for power at stationary, temporary locations that are difficult to resupply. Portable fuel cells should have minimal resupply requirements and be packable in a soldier's rucksack.

A *wearable* fuel cell would be utilized as a small power source worn on the solider for localized power. The wearable fuel cell provides power to different peripheral devices, such as tactical radios, Global Positioning System (GPS) receivers, and other End User Devices (EUD). The fuel cell can be integrated with the devices via an Integrated Soldier Power and Data System (ISPDS) or power manager configured to allow the user to monitor and manage energy consumption of the peripheral systems as well as fuel level in the fuel cell system.

2. Portable fuel cell systems

Based on the projected use of a portable fuel cell as a battery charger and user input, the continuous power output was identified at $\geq$300 W with a weight target $\sim$14 kg. The power selected was based on a recharge of six 150 Wh secondary batteries at a maximum recharge time of 4 h. Three different fuel cell technologies were developed [15], solid oxide fuel cell (SOFC), reformed methanol fuel cell (RMFC), and direct methanol fuel cell (DMFC) and their performance results are summarized below.

2.1. Portable fuel cell systems test results

Based on the $\geq$300 W, $\sim$14 kg targets, Communications Electronics Research Development and Engineering Center (CERDEC) collaborated with industry to develop three different 300 W man portable systems. Each was tested and the results are shown in Table 1.

All the systems contain an internal battery which is required for start up. The SOFC prototype has the highest power and energy density, while the DMFC prototype system's weight is significantly higher than the other systems.

Based on user interest, the SOFC and RMFC systems were tested as part of a limited user field test. The following feedback was received and is described below.

2.2. Feedback based on limited user test results with portable fuel cell systems

i. System size and weight limited the fuel cells to missions with vehicle access or at a permanent outpost. Although the systems fit in a rucksack, they were still considered too large and displaced other mission required equipment [16].
ii. The fuel resupply logistics were perceived as burdensome vs. other portable power technology such as a portable solar system.
iii. From a logistics point of view the users indicated a preference for propane over methanol. Propane is a fuel utilized globally for various applications, while fuel cell grade methanol has a much smaller distribution network.
iv. Users noted the quiet operation of the devices as a key positive. The systems did generate fan noise but it was significantly quieter than combustion generators.
v. Start up & shut down wait time was a key negative to the users. For the RMFC and SOFC systems, a start up time of $\sim$20 min is required to bring the reformer and stack to the operating temperature.
vi. Not enough test data was obtained to measure the system lifetime. System lifetime is critical to ensure the life cycle acquisition costs are competitive with existing solutions.

2.3. Future portable fuel cell system efforts

Future efforts in portable fuel cells must take into consideration the recent development of a portable 600 W spark ignition generator with multi-fuel (JP-8, gasoline, alcohol, propone, etc.) capabilities while providing acceptable performance, as shown in Table 2.

Table 1
Description of portable fuel cell prototype systems.

Requirement	SOFC	RMFC	DMFC
Max output power	300	300	300
System Weight (no fuel, kg)	14	16	20
Dimensions (cm)	40 × 36 × 20	38 × 30 × 25	29 × 51 × 29
Internal Li-ion Battery (Whr)	165	326	80
Voltage (VDC)	28	28	28
Fuel	Propane	Methanol/Water	Methanol
Runtime	1 lb Propane = 4 h	Cartridge (1.2 L) = 4 h	Cartridge (2 L) = 8 h
Capability	APU only	APU + Battery Charging	APU + Battery Charging
Start-up/Shutdown Time (min)	25/25	20/instant	2/instant
Fuel efficiency (%) (LHV)	22	34	16
Specific Power (W kg^{-1})	22	18	15
Power Density (W L^{-1})	10	10	6.9
Specific Energy (72 h mission, Wh kg^{-1})	720	618	591
Energy Density (72 h mission, Wh L^{-1})	554	423	349

Table 2
Specifications for the multi-fuel generator operated on JP-8.

Parameter	Value
Max output power	1000 W
System weight (no fuel)	15 kg
Fuel efficiency	13%
Specific power	41 W kg^{-1}
Power density	10 Wh L^{-1}
Specific energy (600 W/72 h mission)	848 Wh kg^{-1}
Energy density (600 W/72 h mission)	401 Wh L^{-1}
Noise	53 dB @ 7 m

Although this combustion system has low fuel efficiency (13%) and loud noise (53 dB @ 7 m), the multi fuel capability reduces the logistics requirements and has performed well in user evaluation.

Considering the logistic challenges [6], non JP-8 portable fuel cells have to provide significant weight and volume benefits to be successfully deployed for dismounted soldier applications in the US Army. Future development of portable fuel cells will be focused on JP-8 performance capabilities and increasing the power and energy density.

3. Wearable fuel cell systems

The US Army has leveraged commercial fuel cell efforts to develop systems that can be worn by the soldier. Developing a wearable system does pose considerable challenges over the portable systems including form factor and thermal and acoustic signatures.

Efforts by CERDEC, in collaboration with partners have resulted in DMFC, RMFC, SOFC and chemical hydride based wearable fuel cell prototype systems. System test results and operation are described below.

3.1. Wearable fuel cell system test results

Based on the requirement for a wearable fuel cell system, the test performance of wearable fuel cell systems based on DMFC, RMFC, SOFC and chemical hydride based PEM fuel cell technologies are shown in Table 3.

3.2. Reformed methanol fuel cells systems

RMFC systems utilize an external methanol reformer to produce a H_2 rich fuel stream for use in a PEM stack. Fig. 1 shows the anode fuel setup for such a system.

As shown in Fig. 1, the reformer feed is a mixture of 67% methanol and 33% water. The dilute methanol is converted in the fuel processor according to the endothermic steam reforming reaction:

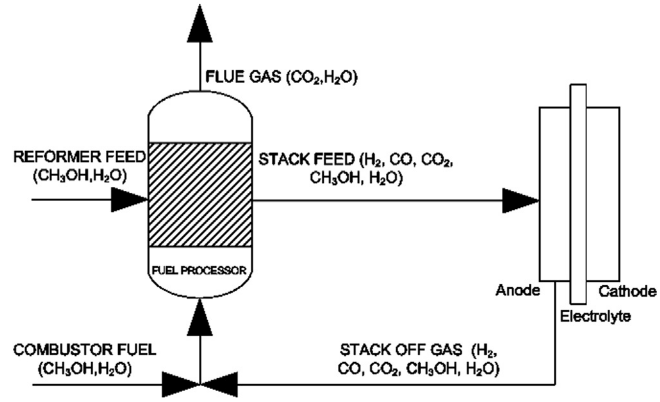

Fig. 1. RMFC anode fuel process flow diagram.

$$CH_3OH + H_2O \xrightarrow{\Delta} 3H_2 + CO_2 \quad \Delta H = 49.5 \text{ kJ mol}^{-1} \tag{1}$$

Low levels of contaminant CO are also formed which must be addressed for high performance [17]. This can be done by purification of the feed with secondary reactions (water gas shift, preferential oxidation) or with a separation device (e.g. Palladium membrane). Alternatively the utilization of a high temperature polybenzimidazole (PBI) based PEM stack that can tolerate higher levels of CO can enable high performance.

The dilute methanol utilized in this system has a fuel energy density of 2910 Wh kg^{-1}. However the system specific energy density, 588 Wh kg^{-1} (72 h mission), is lower due to the balance of plant and packaging of the system. These systems have also demonstrated lifetimes of ~1000 h in laboratory testing [18] and have undergone operational test and evaluation with soldiers [19].

Although the prototype systems have performed to specification and been identified for acquisition for niche applications, widespread adoption has not occurred. User feedback has indicated the form factor is still too large to be worn on the body resulting in systems being utilized for stationary applications.

Future technology efforts include component cost reduction and lifetime improvement.

3.3. Direct methanol fuel cells systems

Direct methanol fuel cells utilize methanol directly in the system with a fuel energy density of 5580 Wh kg^{-1}. However fuel cell stack requirements [20] lower the effective energy density to 394 Wh kg^{-1}, as shown in Table 3. Although 25 W DMFC systems can be utilized for other military applications [21], the resulting power density (13 W kg^{-1}) of a conventional DMFC system is too low for wearable systems.

Efforts to develop a wearable DMFC have focused on system size reduction. This includes utilizing a novel Membrane Electrode Assembly (MEA) with lower methanol crossover while maintaining high proton conductivity [22], resulting in a smaller balance of plant system. As reported previously, a proof of concept system utilizing this novel MEA technology was tested, and the results were promising [15]. There is a doubling in power density and energy density vs. a standard DMFC system, 27 W kg^{-1} vs. 13 W kg^{-1}, and 793 Wh kg^{-1} vs. 394 Wh kg^{-1}, respectively. Recommendations for potential future efforts include developing orientation independence, improving higher temperature performance and ruggedization.

Table 3
Prototype wearable fuel cell systems test results.

Requirement	RMFC	DMFC	SOFC	Chemical hydride FC
Max continuous output power (W)	25	25	60	20
System Weight (no fuel, kg)	1.12	1.92	2.49	0.698
System Volume (no fuel, L)	1.4	3.0	5.3	0.77
Fuel	Methanol /Water	Methanol	Propane	Alane (AlH_3)
Specific Power (W kg^{-1})	22	13	24	28
Power Density (W L^{-1})	23	11	17	32
Specific Energy (20 W, 72 h mission, Wh kg^{-1})	588	394	720	582
Energy Density (20 W, 72 h mission, Wh L^{-1})	463	329	554	667

3.4. Solid oxide fuel cell systems

Although the propane fueled, tubular 60 W SOFC has high power and energy density, the existing system size is too large for a wearable application and requires further miniaturization. Based on the safety risk of using propane on the soldier and the technology risks associated with miniaturizing the technology, adoption of SOFC technology for wearable use has been delayed.

3.5. Chemical hydride based fuel cell systems

Due to the risks associated with compressed H_2 use, the deployment of H_2 PEM systems in the battlefield has not been pursued. However the ability to store H_2 as chemical hydride or a metal hydride [23] provides an alternative to gas storage. Hydride based commercial systems utilizing low temperature PEM stacks are presently available $\geq$1 W [24,25].

Fig. 2 shows the setup of a H_2 fuel feed for a chemical hydride based system. The H_2 is generated from the chemical hydride by heating (thermolysis) or by the addition of water (hydrolysis) [26–28].

Synthesized H_2 dense fuels available include Sodium Borohydride, Ammonia Borane, Ethylene Diamine Borane, and Aluminum Hydride. To design a system, challenges of reaction control (hydrolysis, thermolysis), heat management and H_2 impurities must be considered.

Aluminum hydride (Alane) as a fuel appears especially promising as it produces low impurities and reaction control can be achieved with appropriate process control design [9,26] The α-AlH_3 phase produces 10 wt.% H_2 in an endothermic reaction [Eq. (2)], resulting in a specific fuel energy density of 3300 Wh kg^{-1} based on the LHV_{H_2}:

$$2AlH_3 \xrightarrow{\Delta} 2Al + 3H_2 \quad \Delta H = 6.6 \text{ kJ mol } H_2^{-1} \tag{2}$$

3.5.1. Wearable AlH_3 fuel cell system test results

A 20 W AlH_3 fuel cell prototype system was tested and the results of a constant current test are shown in Fig. 3. The system was operated for 10 h at 20 W and required three cartridge change outs. At a constant current of 1.3 A, the average power drawn was 20.1 W with an average voltage was 15.2 V. Data gaps indicate the time at which cartridge change out occurred. Based on the test results, the specific energy density for a 20 W/72 h mission is 667 Wh kg^{-1}.

The prototype was successfully tested to follow a cycling load from 5% to 100% of rated capacity. This indicates that the system can maintain system control, specifically H_2 production and consumption, while load following. The system was also tested in different orientations and was able to output the test load at the various orientations. Operation at different orientations is necessary for a wearable soldier system.

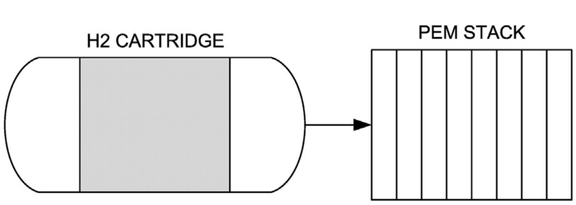

Fig. 2. H_2 fuel feed process flow diagram.

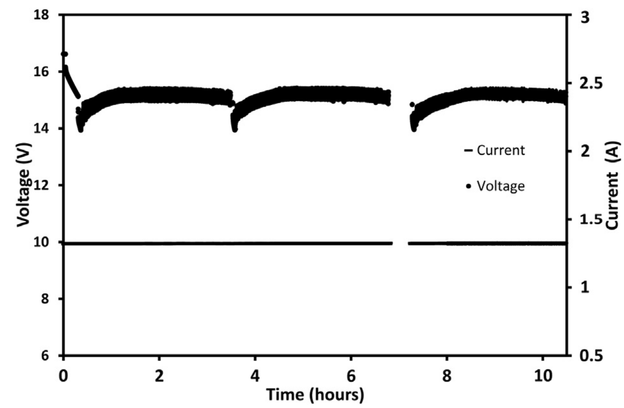

Fig. 3. Constant current test on 20 W AlH_3 system.

Finally, during operation, the surface temperatures were measured to validate that they are below touch temperature specifications for prolonged contact (49 °C) [29].

Despite the endothermic nature of H_2 generation from AlH_3, the system is still able to deliver 33% of the total energy stored in the cartridge to the load as shown in Fig. 4. The heating requirement for a single start up is 11%, subsequent start ups will lower the total energy delivered to the load. The largest loss is due to the inefficiency of the stack. Although there are energy losses, the resulting energy provides a favorable comparison to other fuel cell systems as shown in Table 3.

Table 3 shows that the chemical hydride fuel cell system has the highest power density and energy density compared to the other fuel cell systems. This prototype system has also received positive soldier feedback on the weight (698 g) and volume (622 cm^3) from limited soldier tests. As far as the authors know, this is the highest power density and energy density (20 W/72 h) fuel cell ever demonstrated in a soldier wearable configuration. Compared to other wearable fuel cell systems [11], the performance is significantly higher due to the: high H_2 storage capacity of Alane; use of thermolysis vs. hydrolysis to produce H_2; use of low temperature

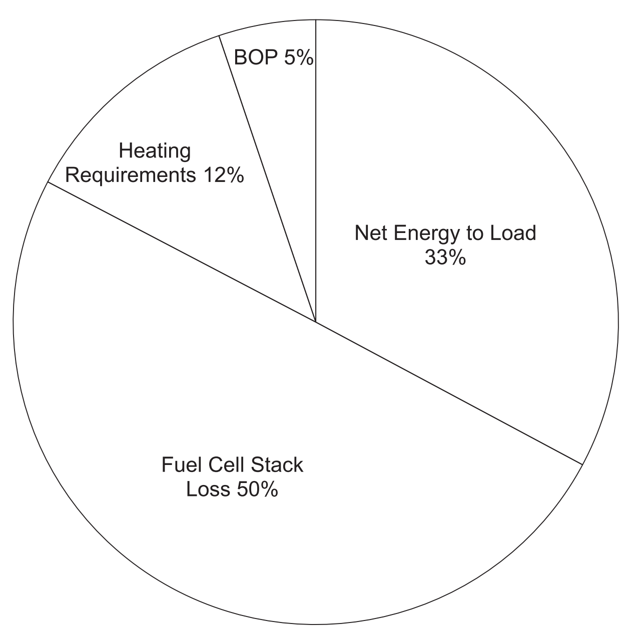

Fig. 4. Energy consumption 20 W AlH_3 fuel cell system.

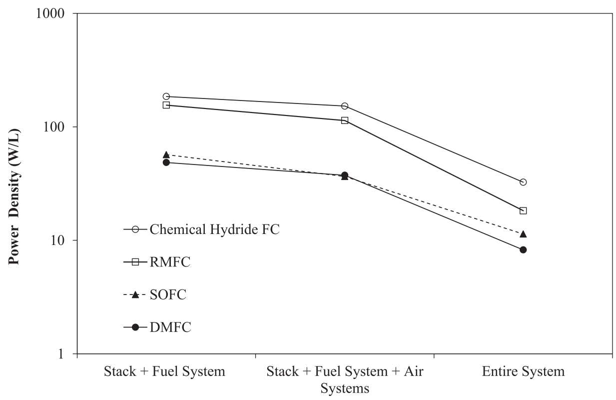

Fig. 5. Power density of wearable fuel cell systems as a function of system components.

PEM stack with a combined cooling and air supply to maximize efficiency and power density.

Future developmental efforts include high temperature operation as well as further improvements in the power density. It should also be noted that as a result of the fuel's synthesis process and low volume requirements, the cost of AlH_3 must be lowered for widespread army deployment.

3.6. Comparison of wearable fuel cell systems

The volume of components in the CERDEC developed fuel cell prototypes is shown in Fig. 5. The chart shows how the power density decreases as the component systems are added. It is noted that for wearable fuel cell systems, the chemical hydride fuel cell and RMFC systems have power densities significantly higher than the SOFC and DMFC systems. The addition of air mover systems for oxidant feed and cooling results in a small decrease in power density. However the final packaging of the system into a wearable form, results in a dramatic decrease in power density. This decrease is a result of BOP components (control boards, insulation) and the void volume in the complete integrated system for a wearable form factor.

3.7. Comparison to batteries

Based on the prototype 20 W AlH_3 system described above, the weight savings vs. a Li-ion rechargeable (127 Wh kg^{-1}) system with no ability to recharge during the mission, is shown in Fig. 6. The potential weight savings of a primary battery based on CF_x chemistry is also shown. Attempts are ongoing to lower the cost of CF_x chemistry to enable widespread Army adoption. The fuel cell system's weight savings is due to the AlH_3 fuel's higher energy density (800 Wh kg^{-1}) vs. the batteries. Due to the high energy density of an AlH_3 cartridge, the fuel cell system demonstrates the greatest weight savings for missions >8 h.

Before Army fielding, a fuel cell system has to meet all the existing soldier use requirements in an operational environment, including ruggedization to withstand drops, vibration, dust and moisture. Although a wearable fuel cell is expected to meet the Army's ruggedization requirements and still provide weight savings, a system is yet to be demonstrated.

A Ragone plot is shown in Fig. 7, as a comparison of the total weight of fuel cell systems and battery power sources for a constant 72 h mission. The 25 W, 55 W and 300 W systems are based on RMFC technology [21]. The 20 W system is based on the prototype AlH_3 fuel cell system described previously. The performance metrics of lithium carbon fluoride ($LiCF_x$) technology [30] are also plotted on Fig. 7 based on manufacture's published specification. It should also be noted that that the discharge rate significantly impacts the battery capacity.

It can be seen that the RMFC and AlH_3 fuel cells significantly outperform the $LiCF_x$ for energy and power density. It is also observed that the power density of the RMFC systems does not change significantly when the output power changes. As expected the energy density for the larger RMFC system is greater than the smaller systems for a constant time.

Currently the AlH_3 fuel cell has the highest power and energy density of all the systems compared, suggesting it is best suited for wearable applications, although advances in methanol fuel cells may alter this. For future Army wearable fuel cell systems, the design challenges for a wearable system are described below.

3.8. Future development of wearable fuel cell systems

The wearable fuel cell design requirements were developed [31] based on U.S. Army requirements and soldier feedback. These specifications include projected needs and lessons learned from previous systems. An example of a wearable power system that has received positive user acceptance is the rechargeable Li-ion conformal battery which is available in rigid [32] and flexible form factors [33].

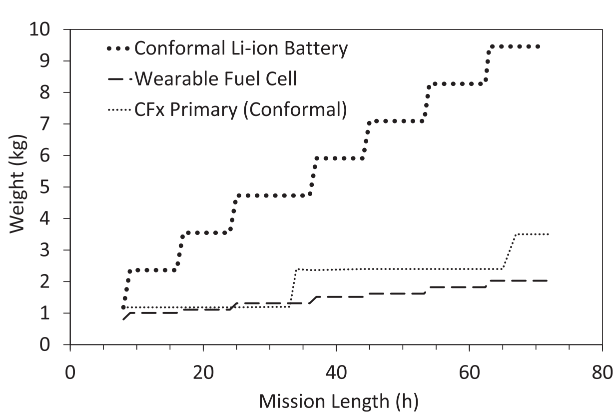

Fig. 6. The benefits of the high energy density AlH_3 system vs. a conformal Li-ion battery when no recharging solution is available and a primary battery based on CF_x chemistry.

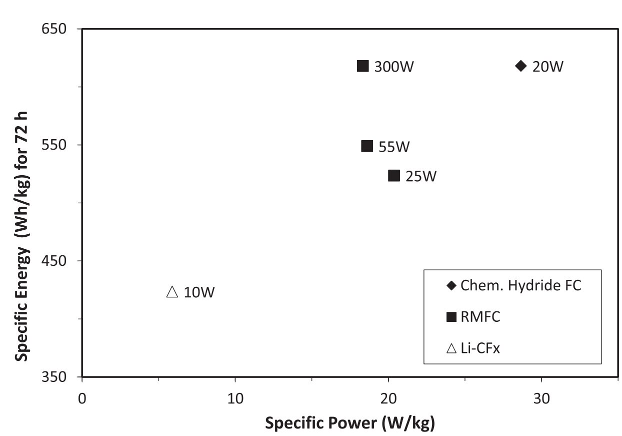

Fig. 7. Ragone plot for a $LiCF_x$ battery, RMFC systems and an AlH_3 based fuel cell. The energy density is based on a 72 h mission at the systems' output power. The system output power is shown next to the data point. All the systems have been through limited user tests.

The wearable fuel cell requirements are based on the future power requirements of a Nett Warrior soldier system. The Nett Warrior soldier system is the low power and low weight advancement of the Land Warrior soldier system [6]. As described earlier in the introduction, the wearable fuel cell will be integrated with other EUDs via an ISPDS, resulting in an objective power requirement of 20 W.

An important design requirement for a soldier mounted system is the ability to wear the fuel cell without impeding access to other gear, while maintaining mobility and comfort resulting in a thickness form factor requirement (not to exceed 1.8 cm). Additionally to minimize snag hazards, the cartridge must be integrated with the stack.

Design goals include operation at high ambient temperatures (55 °C) and minimizing air requirements to allow a fuel cell system to be layered behind other items. This allows items that require ready access, to be layered in front of the power source. The cooling requirement determines the air flow rate and determines the BOP size. Furthermore, there is the requirement for low byproduct heat production to allow for body contact. This results in the requirement for a high efficiency system with highly effective cooling.

Ergonomic factors include an interface that alerts the user to a depleted cartridge and simple, safe, fast cartridge replacement mechanism. Hazards such as unsafe temperature and material toxicity must be mitigated/eliminated for user acceptance.

The use of novel fuels (e.g. chemical hydrides, methanol) presents new challenges for safety as the available operational data with these materials is very limited. Future efforts must address this issue, including military logistic requirements for safe transport and storage.

Finally life cycle costs must be competitive with the incumbent solutions. Preferably the use of fuels (e.g. chemical hydrides) designed for dual use in the military as well as the civilian market will provide the volumes required to be competitive with the existing fielded solutions. Although the cost of fuel cells and the associated fueling infrastructure are a concern, it is expected with appropriately engineered component and production volume, fuel cell systems can provide a competitive total life cycle cost [34].

4. Conclusion

Considering the early military fuel cell prototypes developed in prior efforts (e.g. DARPA Palm Power Effort [7,8]), significant advancements in power density and energy density have been made. Furthermore, to support desired future capabilities in dismounted soldiers, the power requirements are projected to increase, requiring new power source technologies. The continued and successful development of portable and wearable fuel cells can potentially provide the technology to meet the projected needs.

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